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(54) Title: VISION MEASUREMENT AND CORRECTION

(57) Abstract

Automated binocular vision measurement and correction measure the refractions of each eye, the topography of the cornea, and the holographic corneal depth. The computer (407) assesses the visual characteristics and performs optical optimization calculations to determine the optimal corneal shapes that would provide the person with precise vision capabilities. An optimal closed pattern trace of low power level laser energy induces the malaxation of the corneal tissue. Laser energy is delivered to a stromal target (806) in the cornea (805) between the epithelium and endothelium. Predetermined parameters are measured using a moire technique. Data representative of an input fringe pattern which includes signal information of the fringe and noise is filtered in a Fourier transform technique to remove noise and back-ground. In conjunction, pattern normalization is used quantifying data from the pattern.

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VISION MEASUREMENT AND CORRECTION

by

Larry S. Horwitz

BACKGROUND

Improving eyesight is vitally important. Precise measurement and correction of physical characteristics of surfaces including features of the eye is thus also vitally important.

5

Since the Chou Dynasty (circa 479-381 B.C.) man has tried to correct his vision. The measurement of how much correction is required has been a major problem since that time. Typically, in contemporary practice

10 Snellen's charts are used with a phoropter to pragmatically quantify the vision correction. This relies on patient response to quantify the measurement. Auto refractors have been invented that use the knife edge test to quantify the visual acuity via light reflected

15 from the retina. Optical characteristics of the eye are qualified by specific aberrations. Currently, only the first three aberrations of over four hundred are used to correct vision, since this is all that can be measured.

20 Currently, patient refraction measurements require verbal feedback from the patient in order to quantify the refraction measurement. Thus, in order to perform the measurement on both eyes simultaneously, the number of independent variables in the concurrent indi-

25 cators allow too many degrees of freedom that there would be no accuracy in the refraction of either eye. Thus, only one eye can be measured at a time.

A characteristic of the eye is needed in order to track its motion. Methods have been used that scar the cornea and track the scar. Tracking the inside edge of the iris is another technique that has been used, however, the iris diameter changes with ambient light and ocular field of regard. Thus, the error induced as the result of iris tracking is larger then the magnitude of the motion measured leaving it an invalid technique.

This invention relates to measuring the and correcting characteristics or parameters of animate and inanimate elements. In particular, the invention is directed to the measurement of surfaces including inter-faces of features such as the retinal surface of the eye, the corneal topography and the depth of the cornea. Moreover the invention is directed to measuring both animate and inanimate features whether in a stationary state or in motion.

Different techniques have been developed for the accurate measurement of surface characteristics. Often these techniques rely on a laser beam which impinges on a surface and which is then reflected. A relationship between the impinging beam and the reflect-ing beam gives information about the surface character-istics. Where the surface characteristics are other than planar, the determination of parameters about the surface can be more difficult to obtain and analyze. Moreover, where the system relies on a physical interferometric technique, characteristics such as the mechanical stability of the system is critical in order to insure accurate measurement. Another feature of importance is the path length to a subject surface to be measured and a path length to a control or reference. Temporal and

spacial coherence are also difficult to stabilize with conventional physical interferometric techniques.

A different manner from applying interferometry to measure surface characteristics is that which is obtained from a moire' pattern. The invention is particularly related to moire' patterns.

No means exists for accurately determining surface characteristics such as those of the corneal surfaces, e.g., epithelial, Descemet's Membrane and endothelial. Thereby providing keratometric and pachymetric quantified measurements. Moreover, the Applicant is unaware of techniques whereby reflections can be obtained from different surfaces and made to be cooperative such that more specific measurements such as refraction and thickness characteristics of features of the eye can be determined. More specifically, the Applicant is unaware of any known ability to measure and analyze the data from the moire' pattern that are obtained in a manner to apply this data usefully to the object. Such usefulness would include the inherent physical dimensions of a surface, its spacing from another surface, or the degree of movement of the surface or element.

Processing fringe interferometric patterns such as moire' patterns to provide measurement characteristics of a surface is valuable. The invention also relates to the processing of fringe patterns generally and specifically, moire' patterns. More specifically, the invention is directed to the processing of fringe patterns containing information concerning characteristics related to the retinal surface, epithelial surface and endothelial surface of the cornea. With such information, valuable

refractive and diffractive characteristics of the eye can
be measured.

Fringe patterns are caused by an interfero-
metric process. In one form of such process, a colli-
mated light beam is divided so that part of the beam is
directed towards a reference and another towards a
target. Reflections from the reference and target
interfere to provide an interferometric pattern. Inter-
pretation of the pattern can provide measurement charac-
teristics about the target.

Another form of interferometric pattern is
generated, a moire' interferometric fringe pattern, is
by the interference formed when two grating-like trans-
parencies, each with similar but non-identical regular
patterns, overlap. The transmission of light through
each grating-like transparency creates images. The
moire' pattern is the image that is generated through the
modulation of the two separated grating transparency
images. The measurement of this pattern can provide
useful information about measurement characteristics of a
surface. This is related to the generation of the light,
where that light is generated as a reflection from a
surface. The surface can be in the eye, and the pattern
is then revealing of eye measurement characteristics.

The fringe pattern can be distorted by noise in
the system generating the pattern. The noise can be
electronically generated, caused by the camera and
optical system used in the measurement, or be background
or spurious light interference. Additionally, different
reflectivity characteristics of th surface unassociated
with the measurement being sought can also impact
accurate measurement. The reflectivity problems could

arise, for instance, where different contrast charac-
teristics of the surface exist. Alternatively, this can
be caused by different background sources directed on the
surface in a manner unrelated to light associated with
the optical measuring system.

The Applicant seeks to provide an improved
technique and apparatus for analyzing fringe patterns.

This invention also relates to ophthalmic
treatment of the cornea so as to improve the overall
refractive characteristics of the eye.

Different techniques are known for treating the
cornea and thereby improving eyesight. In particular,
one technique is known as radial keratotomy. This
technique is based on radial incisions into the corneal
epithelial surface. This changes the shape of the
cornea and thereby improves the refractive characteris-
tics of the eye. Radial incisions around the pupil are
effected by a laser beam so as to improve the overall
refractive characteristics of the eye. Other techniques
include orthokeratology which involves the remolding of
the cornea by placing a contact lens on the cornea so as
to shape the cornea to a prescribed curvature. Other
approaches have attempted thermal treatment with radio-
frequency coils through a saline bath and the use of a
heated wire to perform the shaping.

A disadvantage in radial incisions around the
pupil is weakening the cornea. With time the cornea
loses its reshaped configuration. Applying heat in a
rather broad manner without the ability to direct the
energy definitively to a target can cause undesirable
heat related consequences to other optical features f

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the eye. Additionally, excess energy applied to the cornea can damage the eye through dryness or burning.

There is a need to provide a measurement apparatus, system and method for accurately providing parameters of selected surfaces such as discrete elements of the eye. Similarly, there is a need to provide such information for non-anatomical or inanimate elements such that parameters of the surfaces or elements can be deter-mined more accurately and their position or movement in space measured and monitored.

Also, there is a need to provide a system for precisely treating the cornea to effect shaping of the cornea in a manner to overcome the disadvantages of the prior art.

SUMMARY

This invention provides a system, apparatus, and method for improved measurement of predetermined parameters of an element. The element may be animate such as an eye or an inanimate surface of an element such as a planar or curvilinear surface or an interface of the element or its surface with its surroundings. The invention also provides a system for cornea treatment.

According to the invention the measurement of a predetermined parameter of an element comprises the generation of a collimated light beam and the direction of that beam onto the element. The beam is reflected from the element and is directed through a first grating to develop a synthetic wave front. The synthetic wavefront is directed through a second grating to develop a moire' pattern. Analyzing the moire' pattern provides measurement data of the element.

In a preferred form of the invention, the element is an anatomical surface, preferably a surface or an interface in the eye. Selectively, this is the retinal surface and the analysis provides refractive data about the eye. Where the surface is the epithelial surface the analysis provides topographical data of the cornea. Where it is the endothelial surface, data on this provides, together with the epithelial data, a thickness measurement of the cornea.

In a preferred form of the invention, the data is obtained globally over the corneal surface, corneal thickness and the retinal surface.

In one preferred form f the inventi n the data
is analyzed to determine movement of anatomical features
such as the cornea.

5　　　　In other preferred forms of the invention,
collimated beams at selected wavelengths are directed to
different surfaces and respective moire' patterns are
obtained and analyzed. Preferably, the data for each
surface is collectively analyzed. This gives information
10　　and overall parameters of the surface and the element
defined by the surface.

Also according to the invention, there is
provided means for receiving data representative of an
15　　input fringe pattern, where the fringe pattern is repre-
sentative of measurement characteristics. The data
includes signal information of the fringe pattern and
noise. Filtering means is provided for removing noise so
as to provide a signal information representative of the
20　　fringe pattern. Thereafter, selectively, the signal
information can be scaled to remove further information
representative of differences in contrast about the input
fringe pattern. This provides scaled signal information
representative of a fringe pattern. Demodulation of
25　　either the pre-scaled or scaled signal is affected to
obtain measurement characteristics represented by the
fringe pattern.

In a preferred form of the invention, the
30　　measurement characteristic is the retinal surface charac-
teristics of the eye and the topography of the epithelial
surface and endothelial surface of the cornea. With this
information, refractive and diffractive characteristics
of the eye are obtained. This can permit for correction
35　　by prosthetic devices such as eyeglasses or c ntact

lenses or by treatment of the eye with laser-directed power.

In a further preferred form of the invention, the fringe pattern is caused by a moire pattern. The filtering means is preferably a Fourier transform. The filter effectively scans the input to determine the central frequency and estimates the spectral content of the signal. The input power across the spectrum is then estimated. After the estimations are obtained, this is treated by a filter transfer function computation. Complex multiplying the transform of the input fringe signal with the transfer function, and then inverse transforming the multiplied output provides an output fringe image without noise.

In yet a further preferred form of the invention scaling of the signal is affected to eliminate the effects of different reflectivity about the surface.

Also by this invention, treatment of the cornea is achieved to effect corneal reshaping in a manner to improve the refractive characteristics of the eye. Laser energy is delivered to a target in the cornea to effect heat treatment of the cornea. There is means for generating the energy in a laser beam and for focusing this energy to a selected part in the cornea at a prescribed depth between the epithelial and endothelial surfaces. The energy is adapted to heat a target area and the laser beam traces a selected target path in the cornea. Heating the corneal matter along the path thereby changes the shape of the cornea.

In a preferred form of the invention, the traced path is a closed loop in the form of a Schwalbe's-

like line. The effective " Schwalbe's line" may be a
regular curve or an irregular shape.

Preferably, the heated area is the stromal
region in the cornea, and the laser energy is obtained
from a carbon dioxide laser focused to avoid heating of
the epithelial and endothelial surfaces.

In a preferred form of the invention, the laser
is inter-operative with means for measuring the refrac-
tive characteristics of the eye, the corneal shape and
corneal depth.   As the thermal treatment is imparted to
the cornea, a feedback is achieved such that the optimal
refractive conditions are obtained.

In some cases, both eyes can be treated
substantially simultaneously while a patient views a 3-D
image through a stereoscope.

The moire technique used in this invention
allows for adjustable sensitivity of measurement and
insensitivity to motion of the eye to allow high quality,
quantified ocular aberrations to be measured without
patient response. Near infrared energy of the Nd:YAG
laser of wavelength, 1.06 micrometers, has a high
reflection coefficient in the choriocapillaris and
pigmented epithelium of the retina. If the laser beam is
well collimated when it enters the eye, the reflected
wave front can be analyzed to measure many, and up to
about two hundred fifty six aberrations of the eye.

Other features of the invention are now further
described with reference to the acc mpanying drawings and
detailed description.

DRAWINGS

In the appended drawings like numbers denote like parts.

FIG. 1 shows the system in accordance with the present invention for closed loop automated low energy refractive tissue-therapy for the binocular refractive correction in animals including humans, as depicted here, spectral biometers for the initial measurement of ocular optical characteristics as well as real-time feed back during the automated procedure are present for both eyes as well as the laser sources;

FIG. 2 the invention takes advantage of the spectral reflectance characteristics of the ocular surfaces in the spectral-biometers;

FIG. 3 shows the light path in a spectral-refractor;

FIG. 4 indicates the moire technique for sensing of the wave front reflected from the respective ocular surfaces of interest in the invention;

FIG. 5 shows the keratopographer beam interface with the anterior epithelial surface of the cornea;

FIG. 6 illustrates the light path of the keratopographer beam as it samples the entire epithelial surface of the cornea in a continuum;

FIG. 7 indicates the reflective interaction of the light used in the pachytopographer t measure the entire surface of the Descemet's membrane or endothelium,

this surface is relat d to the epithelial surface to provide the pachymetry;

FIG. 8 shows the optical path of the pachytopographer laser beam;

FIG. 9 is the flow of the algorithm that processes each of the moire patterns as they occur from the light reflections from each of the ocular surfaces of interest in this invention and the ocular characteristics that they provide;

FIG. 10 shows the noise and background filtering technique as used in FIG. 9;

FIG. 11 shows the technique by which the moire patterns are processed in order to normalize the contrast over each entire pattern, this is the final step in processing the pattern before the wave front data is extracted from them;

FIG. 12 indicates the "trackability" of the moire pattern from the eye (these patterns have not been processed as described in FIGURE's 10 and 11) providing an ideal eye tracking system;

FIG. 13 illustrates the low energy delivery optics to the later half of the stroma, this is an f/0.76 beam incident onto the cornea;

FIG. 14 is the power budget when a carbon dioxide laser beam is used in the corneal tissue therapy for refractive correction, this delivery system is not restricted to this laser;

FIG. 15 are the trace patterns f r typical vision aberration, i.e. myopia, hyperopia and astigmatism; and

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FIG. 16 is the closed loop algorithm for the automatic vision correction system with automatic feed back.

DESCRIPTION

Introduction and Overview

5   There is provided a system for automatic closed
loop binocular vision correction.

          The refractions of both eyes of the patient are
measured simultaneously as a three dimensional perception
10   video is viewed. The predominant action changes from the
near field of view to the far field in a contiguous
manner in combination with dark to bright fields. Con-
currently, the shape and thickness of the cornea are
measured continuously throughout the entire extent of the
15   cornea. These measurements are made at the frame rate of
the video camera in the system, e.g., 60 measurements per
second. Anomalies are disregarded. The field distances
and dark shades are temporally correlated with the depth
of field (i.e., near sighted or far sighted) under going
20   investigation.

          After a period of measurement (less than a
minute) the data is manipulated and the complete optical
characteristics of both eyes are known. The optical
25   aberrations of the eyes are quantified in Zernike
polynomials measuring 256 aberrations simultaneously (as
opposed to the 3 aberrations measured in contemporary
refractions). Since the polynomials are orthogonal, the
aberrations are separable and can be treated as such. An
30   optimization optical analysis is performed that treats
the cornea as the deformable element. Simultaneous far
field and near field optimization are performed in order
to optimize the optical capability in both fields and all
intermediate points. Constraints are put on the corneal
35   manipulation in both magnitude and direction of local

displacement and spatial frequency c ntent of the variation. The cornea are then modeled in finite element representations for both structural analysis and heat transport analysis as reported by J. A. Scott in "A finite element model of heat transport in the human eye", Phys. Med. Biol., Vol. 33, No. 2, 227-241 (1988).

These models are then used to determine where to heat the stromal region in order to generate the corneal shape determined. The constrains put on this analysis are that the thermal energy must be applied to the later half of the corneal depth, the trace pattern is to be a closed loop and the temperature rise in the cornea is not to be more than 10° C. The closest fit to the corneal shapes is determined. If the precise shapes are not achievable, optical analyses are performed on the best fit corneal shapes to determine if the figure of merit is within our specifications. If satisfied we go to the next step; if not the two analyses are optimized. This optimization is performed by eliminating the highest order aberrations from the correction. Thus, potentially only 60 aberrations will be corrected. Trace patterns and dwell times along the pattern are now defined for each eye.

Laser gimballing systems directs the laser energy along the prescribed patterns. Through all of this time (roughly, 10 seconds) the eye motion sensor keeps track of the eye motions. If the eyes move, the biometers can still provide the measurements. If the eyes move during the laser tracing procedure, the data is fed into the gimballing system to provide the compensati n. In the case of a radical movement the therapeutic laser system would turn off; then resume again as soon as the tracking of the eyes is re-initiated. As the corneal

malaxati n is induced if the expected bending does not occur, new control laws are developed at each location so that in real time the dwell time of the laser energy is adjusted. As the thermal trace is completed the refrac-
5   tions of the eyes are again measured. If within the limits allowed, the procedure is recorded and stored in the patient file. If on the other hand the refraction measurement falls outside the required limits, the procedure is re-initiated. If after several iterations
10   the limits cannot be met the system indicates the maximum correction achieved and records the results in the patients files.

       The biometers measure the optical wave fronts
15   reflected from the two corneal surfaces and the retina. Spectral reflectance characteristics of these surfaces allow the segregation of the wave fronts so that all optical characterizations can be measured simultaneously. The spectral reflection peaks are as follows:
20

           Corneal epithelial surface   470 nanometers
           Corneal endothelial surface   525 nanometers
           Retinal surface   1060 nanometers.

25   The 1060 nanometer beam is collimated and directed into the eye. It is focused by the corneal media and the lens, reflected from the retina and then exits the eye by the same path. Wave front analysis is performed by passing the light through two Ronchi
30   gratings that are arranged parallel in planes normal to the direction of propagation and rotated with respect to each other in those planes. The resulting moire pattern is imaged on a mat screen and then recorded by a video camera. The recorded image is processed via Fourier
35   transform techniques and the image contrast is normalized

throughout the pattern. Closed form equations are then applied point by point (i.e., pixel by pixel) to derive the shape of the wave front. With the spatial characteristics known, the wave front is then fit to 256 orthogonal Zernike polynomials. Each of the coefficients of the polynomials is then reduced by a factor of one half to compensate for the double pass characteristic of the measurement. Now the optical aberrations of the eye are defined precisely.

An argon ion 470 nanometer laser beam (or any other laser emitting in the 470 nm spectral region) is collimated then passed through an f/1.25 converging lens and directed toward the center of curvature of the cornea. This light is partially reflected form the surface of the cornea. The reflected light is collected by the f/1.25 lens and directed toward the same Ronchi gratings. The resulting moire pattern is spectrally separated from the refractor pattern and processed in the same manner. Since the reflection is from a single surface the double pass effect does not occur and the polynomial coefficients are not divided by 2. This data is the precise topographical description of the corneal surface. This is the keratopographer system.

Since the moire pattern moves with the eye and the pattern uniquely defines the surface of the eye, the pattern can be tracked to qualify and quantify the motion of the eye. Simple eye motion can be characterized by tracking the transverse plane and area tracking in the axial direction. Detailed eye motion tracking is achieved by this technique integrated with the actual analysis of the moire pattern. This eye dynamics sensor is used to track the motions of the eyes during this entire procedure. The subsystem of the invention can be

used in Heads-Up-Display (HUD) system for fine pointing
and tracking mechanisms; mental alertness indicator that
is characterized by eye motion (sporadic or intentioned)
used to detect falling asleep, drug usage or alcohol
usage; video games where eye motion is an interaction
with the game; and in research where eye motion is a
parameter.

The final biometer is the pachytopographer that
measures the corneal depth continuously throughout the
corneal region. The same argon ion laser (or any other
laser producing light in the 525 nanometer spectral
region) also produces a 525 nm beam. By directing the
beam through the same optical (f/1.25) path, as the
keratopographer, a portion of the light is reflected from
the endothelial surface or Descemet's membrane of the
cornea and is provided the same wave front sensing after
spectral separation from the other two beams. This data
is the topography of the endothelial surface. By cor-
relating the endothelial and epithelial topography and
subtracting the pachymetry of the cornea is provided.

The low energy refractive tissue-therapy system
makes use of the thermal effects of light. Photometric
power itself does not cause therapeutic heat. Power
density causes the heating that induces the malaxation of
the corneal stroma tissue, the lamella. The power densi-
ties at the anterior epithelium and in the later half of
the stroma can be chosen by appropriately selecting the
convergence rate, or f-number, of the beam, the power in
the beam and the wavelength of the beam that lies within
any spectral absorption band of the water around the
stromal lamella.

In this invention, the predominant absorption band of water (H_2O) is used. The intent is to heat the lamella via convection rather than the application of photometric energy directly to the tissue (energy applied to human tissue may have negative long term effects, e.g., cancer or mutated tissue). However, this optical configuration can be applied to any optical delivery system used in thermokeratoplasty (TKP) or photo-thermokeratoplasty. There are other absorption lines 2.6 micrometers, 3.9 micrometers and 6.05 micrometers according to M. A. Mainster in "Ophthalmic applications of infrared lasers-thermal considerations", Invest. Ophthalmol. Visual Sci., Vol 18, No. 4, 414-420, (1979). Lasers operating in these regions are also useful for this application. There are two absorption bands, at 1.3 and 3.4 micrometers, which are strictly for the lamella. Though use of this wavelength is not recommended in this invention applications of lasers of these wavelengths will also make use of the optical delivery system in this invention for the most effective TKP application.

The therapy beam is pointed to the later half of the stroma with a f/0.76 beam. The pachytopographer and keratopographer data are used to correctly position the beam to the 0.25 millimeter accuracy. Using a carbon dioxide laser the power incident on the eye is 0.2 watts with an intensity of less than 5 milliwatts per square centimeter, which when partially absorbed in the stroma causes no malaxation of the lamella. The focus of the beam, and the region where the intensity is high enough to induce the lamella malaxation, is a spherical volume 25 microns in diameter. Less than a microwatt arrives at the Descemet's membrane and endothelial surface of the cornea. The laser is gimballed by x,y,z linear m tor

drives under the control of the computer algorithm that
derived the trace and using the data from the biometers.

Detailed Description

5   FIG. 1 schematically shows an embodiment of the
invention. This figure can be split into two monocular
systems thereby proceeding with one eye at a time. The
subject 00 looks into the system and view two displays 1
10   simultaneously, i.e., one with each eye 10. The displays
are viewed via the reflections from the two beam split-
ters 3 and 2. A three-dimensional dynamically moving
scene is provided the subject since each of the displays
is playing a video of separate cameras having the per-
15   spective if each eye. An example of this is illustrated
in 11 and 12 with the birds flying from far away toward
the subject. The subject is told to watch the moving
objects in the scene thus he is adjusting his focusing
field over a wide range. As the depth of field is
20   changing, the target brightness and contrast is changing.
All of these parameters are temporarily correlated to the
biometers to accurately calibrate the refraction measure-
ments being made.

25   In FIG.2 the spectral reflectance character-
istics of the eye 101 are illustrated. Assume a wide
spectral band white light source 102 illuminating the
eye. A predominant spectral region of the light will be
reflected from each surface of the eye. The cornea 103
30   has two surfaces of interest and the retina 108 provides
the reflection for the optical system sampling wave
front. Though there is specular reflection at each
surface there is a spectral resp nse embedded in each
reflection. Thus, at each surface there is a different
35   "color" reflected. Spectral reflection 104 from the

anterior epithelial corneal surface is n minally 470 nanometers. Descemet's membrane and the endothelial are at the back surface of the cornea. Peak spectral specular reflectance 105 occurs at 525 nanometers. The lens 106 has two surfaces which can reflect energy 107 in the yellow spectral region. Finally, the retina 108 reflects 109 very strongly in the 1060 nanometer region.

The Neodymium:YAG, diode or other laser producing energy in the 1060 nm spectrum and collimator 4 in FIG. 1 provides the collimated beam 5 (dash-dot line) that is equally divided into two paths toward each eye at the beam splitter 6 then directed into the right and left eyes via fold mirrors 7 and 8, beam splitter 9 and beam combiner 3. The collimated beams pass through the optics of the eyes (or, single eye in the case of a monocular system), reflect from the retina and pass back through the eye optics and is directed back to the moire wave front analyzer 21.

This optical path is shown in FIG. 3. The collimated beam 301 reflects from the aperture sharing element 302 and is directed into the eye passing through the cornea 303, the lens 304 and on to the retina 306. It then is reflected out of the eye and this time passes through the aperture sharing element 302 on its way 307 to the wave front sensor.

The wave front sensor is schematically illustrated in FIG. 4. The wave front to be measured 401 enters the sensor and passes through two gratings 402 and 403. The gratings are in parallel planes that are rotated an angle O with respect to each other and axially displace a distance d. The resulting moire pattern 404 is visible on the matte screen 405 and imaged by the

22

camera 406.   If the incoming wave front is as referenced
and unperturbed A (dotted line) will result in a moire
pattern as illustrated by pattern A.   When there is
aberration in the wave front as in B (solid line), an
5   example of the moire pattern is given in B.   The computer
407 then analyzes the wave front.

        In FIG. 1, the path of the 1060 nm beam to the
computer image via 22 then the analyzed beam provides the
10   objective refraction measurement of the eyes, 25.   The
analyzed wave front is temporally coordinated with the
focus require by the video programming, as indicated by
23, to assess the entire field and contrast acuity and
accommodation.

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        In order to provide keratopographical measure-
ments of the cornea of eye 10 a coherent light source
producing radiation in the 470 nanometer region is
required.   In FIG. 1 13 is that radiation source. Light
20   beam 14 (dashed line), the collimated coherent beam from
13, is divided into two beams at beam splitter 16 and
directed toward each eye via fold mirrors 17 (left eye
only), 18, beam splitters 19, through the nulling lenses
20 and beam combiners 3.   Light reflected from corneal
25   epithelial surfaces is directed back through nulling lens
20, through beam splitters 19 into the moire' wave front
analyzer.

        In FIG. 5 the collimated beam 501 (14, FIG. 1)
30   is focused by nulling lens 502 (20, FIG. 1) such that the
converging light 506 is focused near the center of the
radius of curvature of the cornea 503, r (505), of the
eye 504.   Light specularly reflect f rm the corneal
surface will be referenced to the focus of 502 as the

reflected light 501 (left hand pointing arrows) is directed t ward the wave front analyzer.

Three colors will be incident onto the wave front analyzer. In order to analyze each wave front spectral filters are used on the camera focal plane of separate from the camera, in which case three cameras will be required in 21, FIG. 1.

Keratometric measurements are made with the optical system in FIG. 6. Collimated 470 nanometer light 602 (14, FIG.1) is partially reflected from beam splitter 603 (19, FIG.1) and directed onto the eye as previously described. Reflected light partially passes through the beam splitter 603 and 606 toward the wave front analyzer.

Pachytopographical data is measured by measuring topographical data from the Descemet's membrane and/or endothelial surface. Data is correlated with the keratopographical data to obtain the pachytopographical data.

In FIG. 1 525 nanometer spectral band light 15 (dotted line) is obtained from 13. An Argon Ion laser can be used as the source of both 14 and 15. Light 15 is divided toward each eye via the same optical path as 14. Upon reflection from the endothelial surface and/or Descemet's membrane 15 traces the same optical path (except for wave front variations due to the respective reflection surfaces) to the wave front analyzer.

In FIG. 7 the path of the 525 nm band light, pachytopographer beam, indicates the input beam 701 (15, FIG. 1) is focused by the nulling lens 702 (20, FIG. 1) toward the center of curvature of the cornea 705 (505,

2 4

FIG. 5). Light 701 passes through epithelial surface 703
specularly reflects from the endothelial surface and/or
Descemet's membrane 707. Reflected wave front 701 (left
hand going arrows) are referenced to the focused wave
front of 702.

Optical system of pachytopographer is schema-
tically shown in FIG. 8. Measurement beam 801 (701, FIG.
7) is partially reflected from beam splitter 802 (19,
FIG.1) toward eye, as described in FIG. 7. Specularly
reflected light partially passes through 802 with the
output wave front 807 directed toward the wave front
analyzer.

Methodology for analyzing moire' patterns to
describe the ocular parameter of interest is schemati-
cally shown in FIG. 9. After the patterns at the three
different wavelengths are spectrally segregated, patterns
are filtered with respect to noise and spurious back-
ground. It is necessary to normalize the pattern
contrast that is a result of surface reflectance and
transmission inhomogeneity. Patterns are then reduced
to analytic wave fronts, Oster, et al., in "Moire'
Patterns", Scientific American, May 1963, pp. 54-63.
With respect to the pattern analyzed, the surface or wave
front of concern is provided. Keratometry data is
correlated with Descemet's membrane and/or endothelial
surface data to provide the pachymetry data.

In FIG. 9, the input moire' pattern 908 is
directed to block 909 which is the filter to remove noise
and background. The moire' pattern 908 can be shown with
fuzzy light and dark regions. After filtering in block
909, the pattern becomes discrete and separate dark and
light lines as indicated in block 910. As can be seen,

the dark lines have different degrees of darkness which is caused by different surface reflectivity and/or transmission characteristics with respect to the element being measured. The signal is represented by block **910**, is directed then to the means for removing information representative of differences in contrast about the fringe pattern as indicated by block **911**. This effects scaling of the fringe pattern to provide a signal as indicated in block **912** which represents dark lines of equal intensity. The output signal **912** is directed to means for demodulating the scaled signal information of the fringe pattern to obtain measurement characteristics represented by the fringe pattern, such demodulating means being generally indicated by block **913**. From block **913**, the different characteristics of refraction, epithelial surface, and endothelial surface measurements can variously be obtained as diagrammatically illustrated through arrows **914**, **915** and **916**, respectively. The information can then be further processed appropriately. The refraction information can give aberration analysis. The epithelial surface information can give keratometry data, and the information about the epithelial surface and endothelial as indicated collectively by arrows **917** and **918** can be used to give pachymetry data. The representations of the demodulated signal information can be received multiple time over a short temporal period. Anomalies are eliminated and there are means to average the multiple representations to obtain an appropriate output signal **914**, **915** and **916** representative of the measurement characteristics.

The methodology of filtering to eliminate noise and background from the respective pattern is shown in FIG. 10. Local areas of the pattern are chosen with respect to the spatial variation of the noise and

background. With respect to each local area a guard band is·ch sen encompassing it in order t transform the data to the spatial frequency domain using a Fourier transform. The fundamental frequency of the domain is that provided by the configuration of the moire' wave front analyzer. A noise and background power spectrum data is then estimated and combined with the signal estimation to provide the complex transfer function H. Spatial frequency data of the noise/background free pattern, P, is defined by the complex product of the input pattern power spectrum and the transfer function. An inverse Fourier transform of P is the output moire' local area pattern. Local area patterns are then moved throughout total pattern in order to effect the entire moire' pattern.

In FIG. 10, the input moire' local area pattern **1000** is directed into a block **1001** for effecting a Fourier transform of the input and pre-processed moire' pattern. The pattern in the spatial frequency domain is represented by $M(jw_x, jw_y)$. The output from the Fourier transform is indicated as a signal. The signal is directed to means **1002** for estimating the signal spectral content as indicated by $f_o = p/(2\sin 0)$. The output from block **1002** provides a signal as indicated by $S'(jw_x, jw_y)$.

Secondly, there are means **1003** for estimating the input power spectrum and the representation on spatial domain component is indicated by $|M'(jw_x, jw_y)|^2$. Both these estimations are directed as indicated by arrows **1004** and **1005** to a filter transfer functions block **1006** where a computation is effected to provide an outlet signal represented as:

$$H(jw_x, jw_y) = \frac{|S'(jw_x, jw_y)|^2}{|M'(jw_x, jw_y)|^2}.$$

Normalized pattern contrast is achieved via the methodology describe in FIG. 11. Spatial intensity characteristics of the pattern are determined. A window dimension is then determined. Window is then moved throughout the pattern in which a maximum and minimum intensity at each location is determined. The pixel value p(x,y) is then adjusted to the normalized value p'(x,y):

$$p'(x,y) = \frac{p(x,y) - p(min)}{p(max) - p(min)}$$

for all (x,y) within each window (block **1120**).

The noise free moire' pattern image **1111** is directed along line **1112** to a circuit **1113** to determine the centroid and variance of all the pattern p(x,y). The output data **1114** is directed to block **1115** where the local area window size is determined in order to locally adjust for contrast inhomogeneity. Window **1116** is then moved throughout the entire pattern **1117** locally determining the maximum, p(max), and minimum, p(min), pixel values (intensity) within the window **1118**. This data is then passed **1119** to the normalizing equation for every point (x,y) within the window **1120**. Output pattern is now normalized in contrast (as indicated in FIG. 9, **912**).

Effectively, the compensation means includes means for dividing the fringe pattern p(x,y) into discrete pixels and means for defining a neighborhood about each pixel and means for collecting data within that neighborhood, the neighborhood being that data within the window. There are also means for computing the minimum and maximum contrast signal as

indicated by block **1118** within the neighborhood or window
and then the means is scaled to produce a scaled value of
the pixel within the neighborhood as indicated in block
1120.

5   This signal is suited for wave front
analysis and pattern tracking.

          Moire' patterns derived from the corneal
10   epithelial surfaces provide a characteristic by which the
eye can be tracked as shown in FIG. 12. In plane
tracking of the centroid of the pattern provide coarse
tracking of eye to within 1.41 pixels. Analysis of the
patterns provides the fine tracking algorithm. Area
15   tracking of the pattern provides axial translation with
pattern analysis again providing fine tracking data.

          In FIG. 12, the illustration indicates the
manner in which tracking can be effected. This is
20   illustrated relative to the axis as depicted in the x,y,z
coordinate system as illustrated in the axis diagram to
show three dimensional representations **1200**. The point
of juncture between the x,y,z axis is the 0 indicator.
The moire' pattern as indicated in the x,y plane **1210**
25   shows the effect of the relative movement when at the
intersection 0 the pattern **1201** is represented. Movement
to the left is indicated pattern **1202** and movement to the
right along the wire plane is indicated by pattern **1203**.
Movement along the z axis **1211** into and away from the x-y
30   plane **1210** is indicated such that movement away from the
x,y plane is indicated by pattern **1204**, movement at the
intersection by the 0 position, and movement from the
intersection out of the paper by pattern **1205**.

Compound movement being a combination of movement in the x,y and z planes as indicated by arrow 1212 causes a representation 1207. Further movement is indicated by arrow 1213 which gives you a representation 1206. Movement as indicated by arrow 1214 gives you a representation 1208 and further movement is indicated by arrow 1215 which gives you a representation 1209.

In application to the refractive tissue therapy system, the location is fed back to the computation system on 22 FIG. 1 and the laser gimballing 24 FIG. 1.

A mechanism of delivery of low energy refractive tissue therapy is shown in FIG. 13 (26 FIG. 1). The input beam 1301 (27 FIG.1) is focused by a f/0.76 (or similar) lens 1302 to the later half of the corneal 1305 stromal region 1306 to a spot 1307 20 to 50 micrometers in diameter (assume a spherical volume). Therapy be is focused such as to not deliver the energy density to the corneal epithelial surface 1303 or the endothelial surface 1309 that will induce enough thermal energy to cause malaxation of the tissue. Malaxation is only induced in volume 1307. Gimballing (x,y,z) of the therapy beam is performed for local treatment throughout the entire cornea, as discussed later. In the case of a carbon dioxide (CO_2) laser the power budget of the therapy beam is shown in FIG. 14. Though 0.2 watts is incident upon the eye, power density is low enough that malaxation will not occur. At the focus around the 20 to 50 micrometer diameter volume the power density is high enough to induce the 10° C elevation of temperature. At the endothelial surface the intensity will not cause endothelial cell damage.

Typical and representative trace patterns of the therapy beam is illustrated in FIG. 15. It is evident that the patterns form a pseudo Schwalbe's line. Schwalbe's line holds the cornea erect in the spherical

5 form. By forming a closed loop trace pattern 1502 a,b & c the corneal malaxation has shown to provide a steady state form of the cornea post-malaxation. As representative, trace 1502a will provide a correction of myopic sight impairment. Likewise 1502b hyperopic correction

10 and 1502c is a correction for this arbitrary astigmatism.

The invention performs the high order corrections utilizing a thermal corneal tissue therapy technique in conjunction with optical and corneal

15 structural analysis.

In FIG. 16, the automated system is illustrated in a closed loop. With incoming data providing the refraction impairment, keratometry and pachymetry

20 from the biometers (1601, 1602 and 1606, i.e., 22 and 23 in FIG. 1), optimization for the corrected ocular optical system is determined by least squares fitting the measurements (who are themselves locally discriminated and averaged) to a discrete number of Zernike polynomials

25 in the optical optimization processor 1615 (in computer 25 FIG. 1). Desired corneal shape is derived (given spatial constraints), or contact lenses of spectacles are defined (1618). In the case of corneal therapy, a finite element model of the cornea is developed form the kerato-

30 metry and pachymetry data in block 1616. Thermal therapy is then defined by the thermal analysis in block 1617 as to locations of the therapy, i.e., laser beam trace, and dwell times of the beam at each site (1621 and 24 in FIG. 1). For medical acceptability the data is displayed in

35 block 1619. Spatial coordinates of the beam are the

given 1620 to the gimballing system 1615 to trace the
cl sed loop trace. As well, l cati ns of the eyes are
provided via the keratopographers 1602 and the tracking
algorithm 1614 in real-time on line 1613 into the loca-
tion file 1614 for the thermal therapy gimballing system.
Upon gimballing completion the optical characteristics of
the eyes are again measured 1601 and 1602. If criteria
are passed for the optimal patient visual correction in
block 1603, the data is passed 1604 to block 1605 where
it is recorded and the procedure is complete. On the
other hand if the criteria is not passed, the new data is
passed back through the system, i.e., to blocks 1609 and
1608 (the current pachymetry is again measured 1606 and
provided to block 1607) to initiate a new iteration of
the corrective procedure. Thus, closing the vision
correction control loop.

The system as indicated operates in a closed
loop to effect optical measurements and also to determine
the degree of corrective treatment that is necessary for
the optical element. When the optical treatment is
effected, the closed loop can provide different refrac-
tive signals and this can be adapted so that ultimately
the optical conditions are rectified.

The invented spectral-refractor system requires
no patient conscious feed-back. Thus, a binocular
refraction can be performed. The corneal topography and
the corneal holographic depth measurement require no
patient feedback. Therefore, all of the parameters of
the patient's visual characteristics can be measured
simultaneously in a binocular mode.

Corneal global topography is a mechanism needed
to sample (i.e., make measurements from) the entire

surface of the cornea. By combining ocular spectral reflectance information with wave front sensing techno-logy, the corneal surface topography is precisely and continuously measured. Such measurements will provide precise biometrics in order to fit contact lenses and to analyze the cornea for refractive surgical or therapeutic procedures.

The technique used in the keratometric method permits the dynamics of the eye to be tracked, i.e., an eye tracking sensor. This can qualify eye motion or quantify it to 200 microradians (or, 0.01 degree).

This technique is useful in ophthalmic surgery, refractive surgical and therapeutic procedures, pointing and tracking in helmet mounted systems, sensors to deter-mine if a person is falling asleep (e.g., automobile sleep alarms), mental acuity tests (e.g., alcohol and drug tests), and video games in which eye tracking would be used as the interaction with the game.

Laser energy with the appropriate spectral absorption characteristic of the stromal region in co-ordination with the optical delivery system produces the therapeutic effect needed to induce refractive altera-tion. Corneal stromal region temperature must be ele-vated by 10° C in order to produce the malaxation as can be derived from E. L. Shaw and A. R. Gasset in "Thermo-keratoplasty (TKP) Temperature Profile", J. Invest. Ophthalmol. 13, No. 3, 181-186 (1974), and J. A. Scott in "The computation of temperature rises in the human eye induced by infrared radiation", Phys. Med. Biol., Vol. 33, No. 2, 243-257 (1988). Temperature rise is con-trolled by the dwell time of the focus of the laser beam. Corneal shape change is controlled by the trace pattern

of the gimballed laser beam. This is a low energy refractive tissue technique. An automated, closed loop control refractive correction system, integrates this with the spectral refractor, the keratopographer, the pachytopographer, and the eye dynamics sensor.

Software performs optical analysis of the eye, and structural and thermal analysis of the cornea. This is a closed loop, ophthalmic system. No conscious patient feedback is required for the system to perform. Thus, the system can be used for any mammals, e.g., veterinary, mentally retarded patients, patients who are too young to communicate or are otherwise unable to communicate.

The invention seeks to perform closed loop refractive correction to both eyes of the subject patient simultaneously and automatically. No subjective feedback from the patient will be required by the system. While viewing a three dimensional dynamic video scene, the patients ocular parameters will be measured, calculation performed and thermal refractive tissue therapy performed. The system is closed loop in the sense that if the procedure does not produce the desired refractive and corneal effects desired, it compensates for the errors automatically.

Automatic, binocular or monocular refractive measurements of the vision of subject patients without causing eye strain or requiring verbal response should be possible. Contact lens or spectacle lens prescriptions will likely be provided automatically as well as pre-scribed refractive surgical or tissue therapeutical procedures.

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Precise topographies of corneal surface to be used in contact lens fitting, analysis of c rneal scaring and lesions, ophthalmic research, and refractive surgical and tissue therapeutical procedures should be possible.

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Holographic topographies of the corneal depth may be used in ophthalmic research, refractive surgical and tissue therapeutical procedures, and corneal diagnostic analysis.

10

Quality control of inanimate elements such as objects where the surface of the product is an indicator of the product quality is possible. Examples are ball bearings or golf balls where the sphericity is important, optical components where surface quality is important, injection molded elements where surface quality is important, and cut gem quality where the relative position of cut faces are important.

20

Many more examples and applications of the invention exist, each differing from the other in matters of detail only. The invention is to be considered limited only by the following claims.

CLAIMS:

1. Apparatus for measuring a predetermined
parameter of an element comprising:
   (a) means for generating a collimated
light beam;
   (b) means for directing the beam onto the
element wherein the beam is reflected from the element;
   (c) means for directing the reflected
beam through a first grating to develop a wave front;
   (d) means for directing the wave front
through a second grating to develop a moire' pattern; and
   (e) means for analyzing the moire'
pattern to produce measurement data of the element.

2. Apparatus as claimed in claim 1 including
a nulling converging lens between the element and the
first grating, the nulling lens having related to the
surface of the element to provide a beam front substan-
tially parallel to the surface of the element.

3. Apparatus as claimed in claim 1 wherein
the analyzing means includes computation means for
removal of noise and for determining a substantially
noise-free moire pattern thereby to provide measurement
data of the element.

4. Apparatus as claimed in claim 1 including
means for selecting a collimated beam of a predetermined
wavelength suitable for reflection from a selected
element.

5. Apparatus as claimed in claim 4 wherein
the beam has a wavelength in the range of about 400 t
about 1100 nanometers.

6.   Apparatus as claimed in claim 5 wherein the wavelength is about 1060 nanometers and wherein the beam is directed onto a retinal surface of an eye thereby to permit measurement of refractive characteristics of the eye.

7.   Apparatus as claimed in claim 4 wherein the beam is a Nd:Yag laser beam.

8.   Apparatus as claimed in claim 4 wherein the beam has a wavelength in the range of about 400 to about 500 nanometers, and wherein the beam is directed onto an epithelial surface of a cornea of an eye.

9.   Apparatus as claimed in claim 8 wherein the wavelength is about 470 nanometers.

10.   Apparatus as claimed in claim 8 wherein the beam is an Argon Ion laser beam.

11.   Apparatus as claimed in claim 4 wherein the wavelength of the beam is in the range of about 500 to about 550 nanometers and is directed to an endothelial surface of a cornea of an eye.

12.   Apparatus as claimed in claim 11 wherein the wavelength is about 525 nanometers.

13.   Apparatus as claimed in claim 11 wherein the beam is an Argon Ion laser beam.

14.   Apparatus as claimed in claim 1 wherein different beams are selectively direct d at different surfaces of selected elements and wherein a first beam is directed at an epithelial surface of a cornea and a

second beam is directed at an endothelial surface of a cornea and wherein the analysis means provides data of the epithelial surface, and data of the endothelial surface, and a measurement of the thickness of the cornea over a predetermined corneal area.

15. Apparatus as claimed in claim 14 wherein a third beam is directed at a retinal surface thereby to provide data relating to the refractive characteristics of the retinal surface, the beam being directed over a predetermined area of the retinal surface.

16. Apparatus as claimed in claim 15 wherein the means for analyzing the moire pattern selectively analyzes data from the beam directed the retinal surface, the beam directed at the epithelial surface and the beam directed at the endothelial surface, the analyzing means thereby providing informational characteristics of the refractive characteristic of an eye as determined by the reflection from the retinal surface, and the reflection characteristics of the eye as effected by the cornea over a predetermined area of the cornea.

17. Apparatus as claimed in claim 16 including means for analyzing the refractive information to provide data for changing the refractive characteristics.

18. Apparatus as claimed in claim 14 wherein the epithelial information is analyzed to provide data about the shape of the cornea.

19. Apparatus as claimed in claim 14 including means for analyzing the epithelial information and endo-thelial information for providing data about the corneal thickness.

20.   Apparatus as claimed in claim 1 wherein the beam is directed at an element surface which is irregular.

21.   Apparatus as claimed in claim 1 wherein the element includes a surface which is essentially curvilinear.

22.   Apparatus as claimed in claim 1 wherein the surface is essentially circular.

23.   Apparatus as claimed in claim 1 wherein the beam is directed at elements having multiple surfaces substantially simultaneously, and including multiple analyzing means for determining multiple characteristics of the elements.

24.   Apparatus as claimed in claim 23 wherein the beam is directed to a second surface and wherein a reflection from the first surface and a second surface is processed by respective analyzing means, and wherein the surfaces are related such that the analyzing means can provide information from both the surfaces thereby to provide interrelated data of both surfaces.

25.   Apparatus as claimed in claim 1 including means for storing data representative of the element parameters.

26.   Apparatus as claimed in claim 1 wherein the analyzing means includes means for tracking relative movement of the element.

27. Apparatus as claimed in claim 26 including means to determine movement in any one of three dimensions.

28. Apparatus as claimed in claim 1 including directing a beam at a predetermined wavelength towards a lens surface of an eye, the wavelength being selected to be reflected from at least one of the interfaces of the lens with its surroundings in the eye.

29. Apparatus as claimed in claim 1 including means for continuously measuring the wavefront of the beam as projected in the pattern thereby to continuously obtain measurement parameters of the surface.

30. Apparatus as claimed in claim 1 wherein the surface is selectively animate or inanimate.

31. Apparatus for processing a fringe pattern, the pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern; and

(c) means for demodulating the signal information of the fringe pattern thereby to obtain measurement characteristics represented by the fringe pattern.

32. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurem nt characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern;

(c) means for receiving the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide a scaled fringe pattern; and

(d) means for demodulating the scaled signal information of the fringe pattern for obtaining the measurement characteristic represented by the fringe pattern.

33. Apparatus as claimed in either claim 31 or claim 32 including means for processing the demodulated signal information thereby to determine wavefront data representative of the measurement characteristics.

34. Apparatus as claimed in claim 33 wherein the measurement characteristics represent three dimensional topographic information.

35. Apparatus as claimed in claim 33 including means for receiving multiple representations of the demodulated signal information and including means for averaging the multiple representations thereby to obtain an output signal representative of measurement characteristics.

36. Apparatus as claimed in claim 35 including means for analyzing and presenting the measurement characteristics.

37. Apparatus as claimed in either claim 31 or claim 32 wherein the input fringe pattern is image data representative of an anatomical surface.

38. Apparatus as claimed in claim 32 wherein the image data is selectively representative of at least one of the retinal surface, epithelial surface or endo-thelial surface of the eye.

39. Apparatus as claimed in either claim 31 or claim 32 wherein the input fringe pattern is a interfero-metric pattern.

40. Apparatus as claimed in claim 39 wherein the input fringe pattern is a moire pattern.

41. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representa-tive of an input fringe pattern;

(b) means for demodulating the data to obtain information representative of a measurement characteristic;

(c) means for obtaining further represen-tations of the demodulated data and for averaging the data to obtain an effective average as an output signal representative of the measurement characteristics;

(d) means for removing anomalies falling significantly beyond the effective average; and

(e) means for analyzing the output signal and presenting the output signal as a representation of the measurement characteristics.

42. Apparatus as claimed in claim 41 wherein the input data is selectively representative of at least one of the surface characteristics of the eye, the surface being selectively the retinal surface, endothelial surface or the epithelial surface.

43. Apparatus as claimed in either claim 31 or claim 32 wherein the demodulation means effectively converts the data into a sinusoidal wave pattern, the sinusoidal wave pattern having phase modulated and frequency modulated characteristics, and wherein the phase modulated characteristics is representative of depth in a topographical sense and the frequency modulated signal is representative of the slope of a surface.

44. Apparatus as claimed in either claim 31 or claim 32 wherein the demodulation means effectively treats a fringe pattern as a continuing communication signal, the communication signal being analyzed by the demodulation means.

45. Apparatus as claimed in either claim 31 or claim 32 wherein the filtering means includes means for selectively analyzing discrete portions of the fringe pattern for determining local noise and background in the discrete portions.

46. Apparatus as claimed in claim 32 wherein the means for scaling provides a scaled fringe pattern, the sealing means selectively normalizing discrete p r-tions of the fringe pattern.

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47. Apparatus as claimed in claim 46 including means for comparing the data before scaling with the data after scaling thereby to obtain information about surface roughness being represented by the measurement character-istics.

48. Apparatus for electronically processing a fringe pattern to obtain measurement characteristics, the fringe pattern being representative of the measurement characteristics, comprising:

(a) means for receiving data representa-tive of an input fringe pattern, the data including signal information of the fringe pattern and noise; and

(b) filtering means for removing the noise thereby to provide the signal information repre-sentative of the fringe pattern, wherein the filtering means includes a Fourier transform based local area filter.

49. Apparatus as claimed in claim 48 wherein the filtering means includes a Fourier transform based local area filter.

50. Apparatus as claimed in claim 49 wherein the receiving data is directed to Fourier transform means, the output of the Fourier transform means being directed firstly to means for estimating the signal spectrum, and secondly to means for estimating the input power spectrum, and means for receiving the first and second spectrum estimations, the receiving means being computation means for a filter transfer function, the output of the computation means being directed to means for complex multiplying the function with the transformed receiving data, and means for receiving the complex multiplied signal and performing an inverse Fourier

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transform thereby to provide an output signal representative of the fringe pattern with noise removed.

51.   Apparatus as claimed in claim 50 wherein
the means for signal spectrum estimation provides an
estimate of a center frequency and an estimate of the
spectral content of the signal, such estimates being an
indication of the signal information without noise.

52.   Apparatus as claimed in claim 50 wherein
the input power spectrum estimation means provides an
estimate of the signal information and noise of the
entire input signal.

53.   Apparatus for processing a fringe pattern,
the fringe pattern being representative of measurement
characteristics, comprising:
             (a)   means for receiving data representa-
tive of an input fringe pattern, the data including
signal information of the fringe pattern and noise;
             (b)   filtering means for removing the
noise information thereby to provide the signal informa-
tion representative of the fringe pattern; and
             (c)   means for scaling the signal informa-
tion from the filtering means and for removing from the
signal information further information representative of
differences in contrast about the input fringe pattern
thereby to provide scaled signal information representa-
tive of the fringe pattern, and wherein the scaling means
is an adaptive surface roughness compensation means.

54.   Apparatus as claimed in claim 53 wherein
the compensation means includes means for dividing the
fringe pattern into discreet pixels, means for defining a
neighborhood about each pixel, means for collecting data

within the neighborhood, means for computing a minimum and a maximum contrast signal within the neighborhood, and means for scaling the minimum and maximum signal thereby to provide a scaled value of the pixel within the neighborhood.

55. Apparatus as claimed in claim 54 wherein the size of the neighborhood is selected to contain at least one fringe maximum and one fringe minimum signal.

56. Apparatus as claimed in claim 54 wherein the fringe pattern is represented by a moire pattern, and the maximum signal is represented by a dark line of the moire pattern and the minimum signal by a space between the dark lines in the moire pattern, and wherein scaling effectively adjusts each pixel to vary between a maximum and a minimum, the maximum and the minimum being applicable to adjacent pixels.

57. Apparatus for delivering laser energy to a target in a cornea region of an eye comprising:

   (a)   means for generating energy in a laser beam at a predetermined wavelength such that energy is absorbed by water;

   (b)   means for focusing the energy to a selected part in the cornea at a predetermined selected depth between an epithelial surface of the cornea and an endothelial surface of the cornea whereby the energy in the laser beam heats the target; and

   (c)   means for tracing the laser beam on a selected path and heating the cornea at selected targets on that path thereby to change the shape of the cornea.

58. Apparatus as claimed in claim 57 wherein the target is in a stroma region f the cornea.

59. Apparatus as claimed in claim 57 wherein the traced path forms a closed loop.

60. Apparatus as claimed in claim 59 wherein the closed path forms a Schwalbe's-like line.

61. Apparatus as claimed in claim 57 wherein the intensity at the target is in the range of between about 0.5 to about 2 watts/cm^2.

62. Apparatus as claimed in claim 61 wherein the intensity is in the range of about 1.1 watts/cm^2.

63. Apparatus as claimed in claim 57 wherein the beam focuses energy at the target to form a diameter of between about 10 to about 50 microns.

64. Apparatus as claimed in claim 63 wherein the focus diameter is about 25 microns.

65. Apparatus as claimed in claim 57 wherein the intensity of the beam at the epithelial surface is about 5 X 10^{-3} watts/cm^2.

66. Apparatus as claimed in claim 57 wherein the intensity at the endothelial is about 2.0 X 10^{-4} watts/cm^2.

67. Apparatus as claimed in claim 57 wherein the laser beam is generated by a CO_2 laser.

68. Apparatus as claimed in claim 57 wherein the laser beam is focused towards the target at a +$^{\bullet}$ number of about 0.76.

69. Apparatus as claimed in claim 59 wherein the traced path is a regular curve.

70. Apparatus as claimed in claim 69 wherein the curve is selectively a circle or an ellipse.

71. Apparatus as claimed in claim 59 wherein the traced path is an irregular curvilinear shape.

72. Apparatus as claimed in claim 57 including means for measuring the refractive characteristics of the eye, means for feeding data representative of the refractive characteristics to the means for tracing the laser beam on the selected path, and means for causing the tracing means to follow a path to provide different refractive characteristics of the eye by changing the shape of the cornea in terms of the traced path and thereby to effect a change of the refractive characteristics.

73. Apparatus as claimed in claim 57 including means for directing a patient to view a three dimensional image through a stereoscope, means for measuring the refractive characteristics of the eyes of a patient, means for measuring the shape and thickness of the cornea of the eyes and means for determining the refractive changes necessary to change the overall refraction of the eyes, and means for delivering the laser beam to the target on a selected path to thereby change the refraction characteristics of the eyes.

74. Apparatus as claimed in claim 72 including computer control means for coordinating the measuring and changing characteristics.

75. Apparatus as claimed in claim 74 including feedback means for continually controlling the laser beam operation and tracing means.

76. Apparatus as claimed in claim 57 including directing the energy to water molecules in a stroma of the eye.

77. Apparatus as claimed in claim 57 wherein means is provided for analytically dividing the corneal region into finite elemental areas, computing means for analyzing relative stress factors between the finite elemental areas, means for determining the heating effect on one or more selected finite elemental areas relative to stress factors between the elemental areas thereby to change the physical relationship between the respective elemental areas and the physical corneal material, and means for directing the application of heat to selected elemental areas.

78. Apparatus as claimed in claim 57 including means for optically analyzing the corneal region in elemental areas, and means for applying a structural analysis technique to the elemental areas to provide information about the effect of applying heat to the elemental areas.

79. Apparatus as claimed in claim 78 including means for applying energy to selected elemental areas as determined by the finite elemental analysis thereby to change the optical refractive system in the eye.

80. Apparatus as claimed in claim 77 wherein the selected elemental areas are the target of the beam.

81. Apparatus as claimed in claim 79 wherein the selected elemental areas are the target of the beam.

82. Apparatus as claimed in claim 73 including means for changing substantially simultaneously the refractive characteristics of two eyes of a patient.

83. Apparatus as claimed in claim 73 including means for selectively viewing images at different depths at different predetermined times, means for obtaining refractive information at the respective predetermined times, means for determining data for changing the refractive characteristics, and means for delivering a laser beam to heat the cornea and thereby change the refractive characteristics according to the determined data.

84. A method for measuring a predetermined parameter of an element comprising:
   (a) generating a collimated light beam;
   (b) directing the beam onto the element wherein the beam is reflected from the element;
   (c) directing the reflected beam through a first grating to develop a wavefront;
   (d) directing the wavefront through a second grating to develop a moire pattern; and
   (e) analyzing the moire pattern to produce measurement data of the element.

85. A method as claimed in claim 84 including converging the beam being related to provide a beam front substantially parallel to the surface of the element.

86. A method as claimed in claim 84 including removal of noise and determining a substantially noise-

free moire pattern thereby to provide measurement data of
the element.

87.   A method for processing a fringe pattern,
the pattern being representative of measurement characteristics, comprising:

(a)   receiving data representative of an
input fringe pattern, the data including signal information of the fringe pattern and noise;

(b)   removing the noise thereby to provide
the signal information representative of the fringe
pattern; and

(c)   demodulating the signal information
of the fringe pattern thereby to obtain measurement
characteristics represented by the fringe pattern.

88.   A method for processing a fringe pattern,
the fringe pattern being representative of measurement
characteristics, comprising:

(a)   receiving data representative of an
input fringe pattern, the data including signal information of the fringe pattern and noise;

(b)   removing the noise thereby to provide
the signal information representative of the fringe
pattern;

(c)   receiving the signal information from
the filtering means and for removing from the signal
information further information representative of differences in contrast about the input fringe pattern thereby
to provide a scaled fringe pattern; and

(d)   demodulating the scaled signal information of the fringe pattern for obtaining the measurement characteristic represented by the fringe pattern.

89. A method for delivering laser energy to a target in a cornea region of an eye comprising:

(a) generating energy in a laser beam at a predetermined wavelength such that energy is absorbed by water;

(b) focusing the energy to a selected part in the cornea at a predetermined selected depth between an epithelial surface of the cornea and an endothelial surface of the cornea whereby the energy in the laser beam heats the target; and

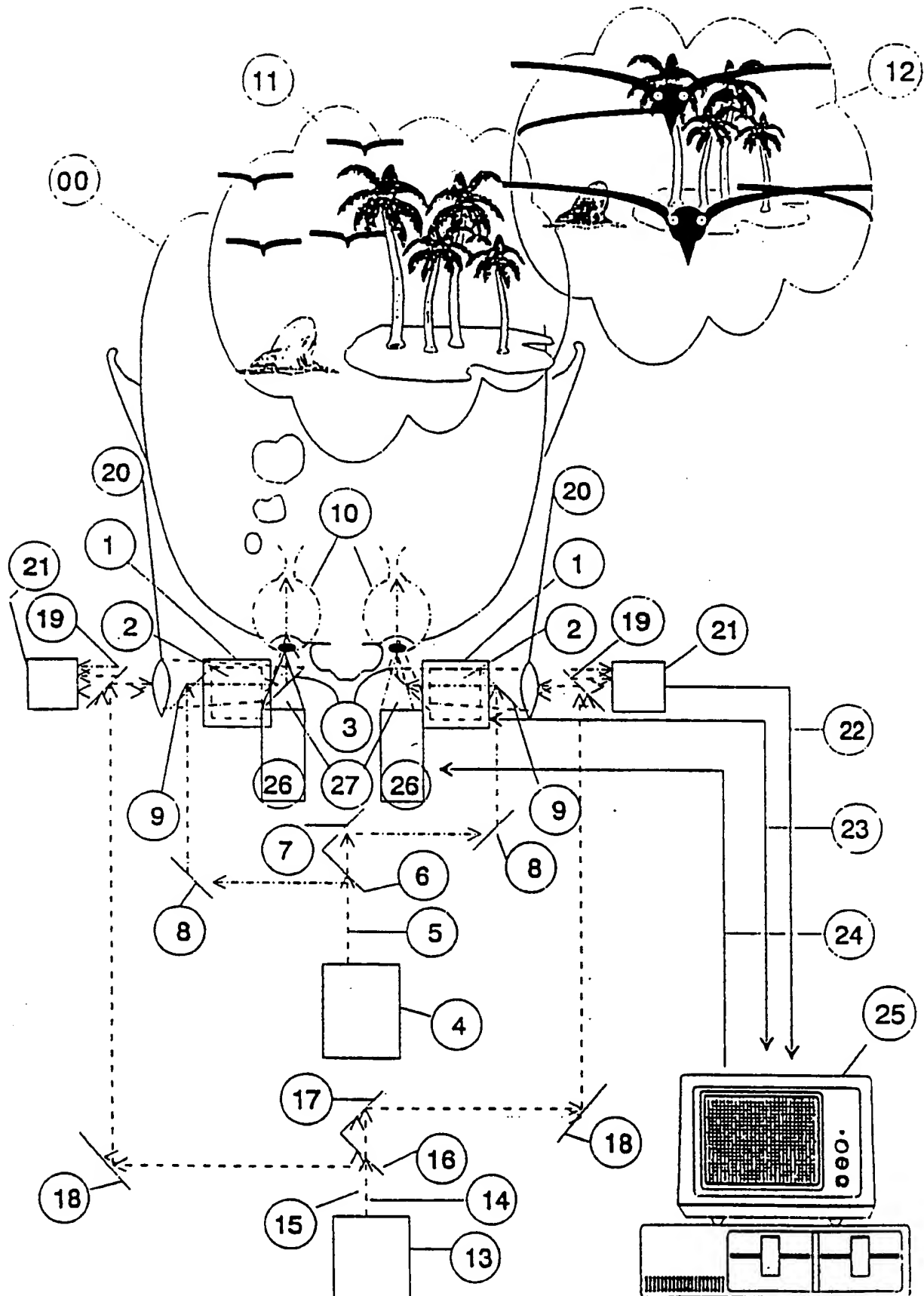(c) tracing the laser beam on a selected path and heating the cornea at selected targets on that path thereby to change the shape of the cornea.
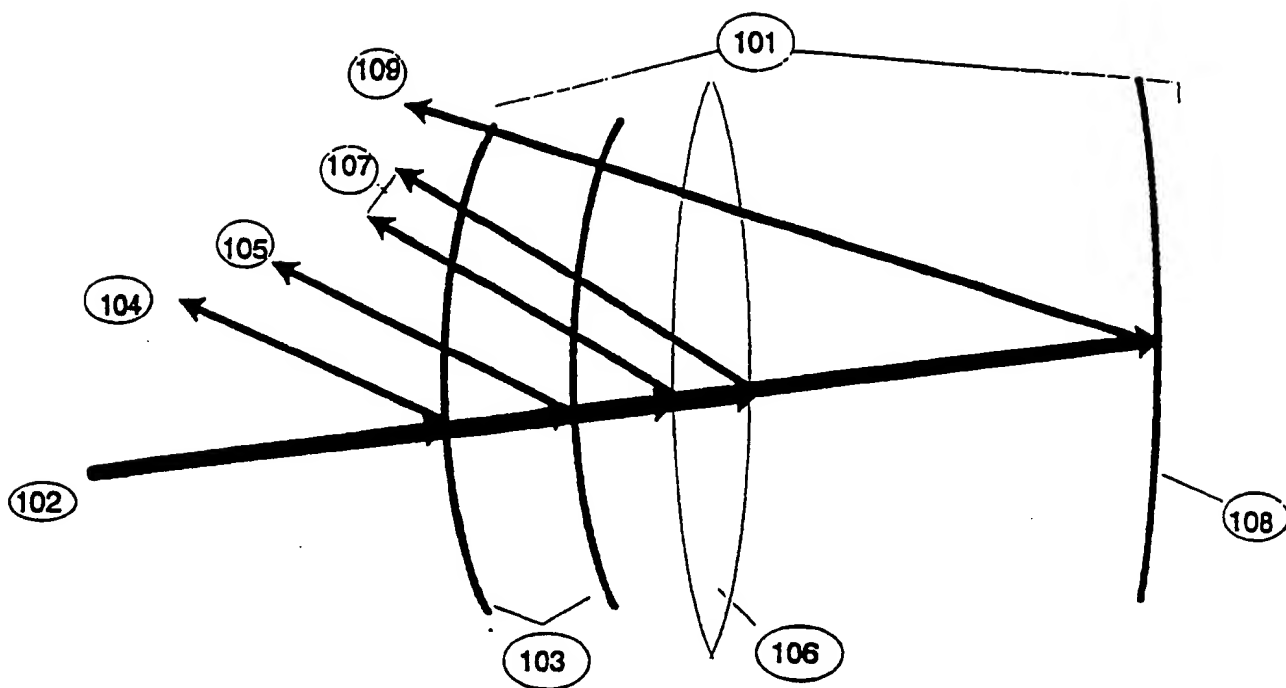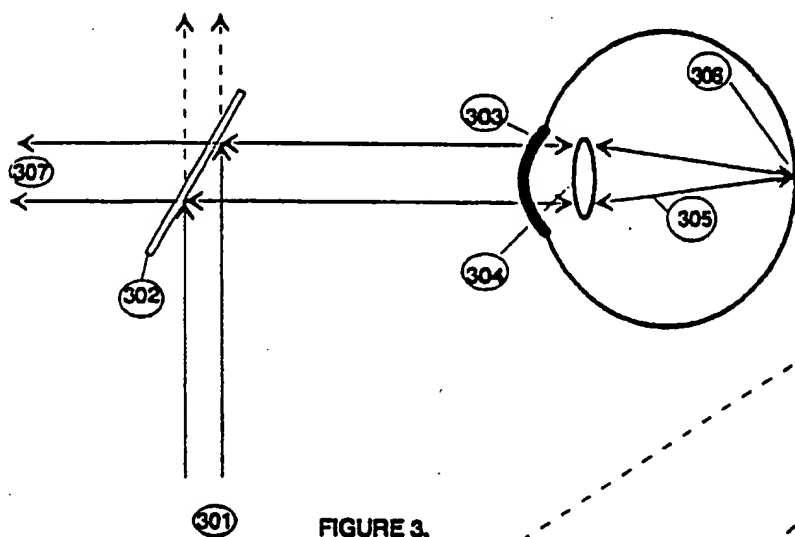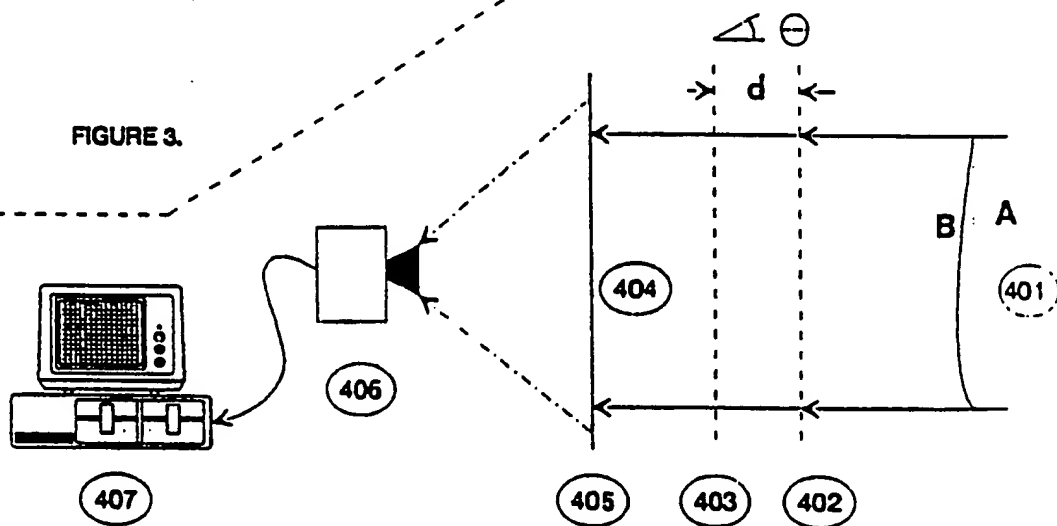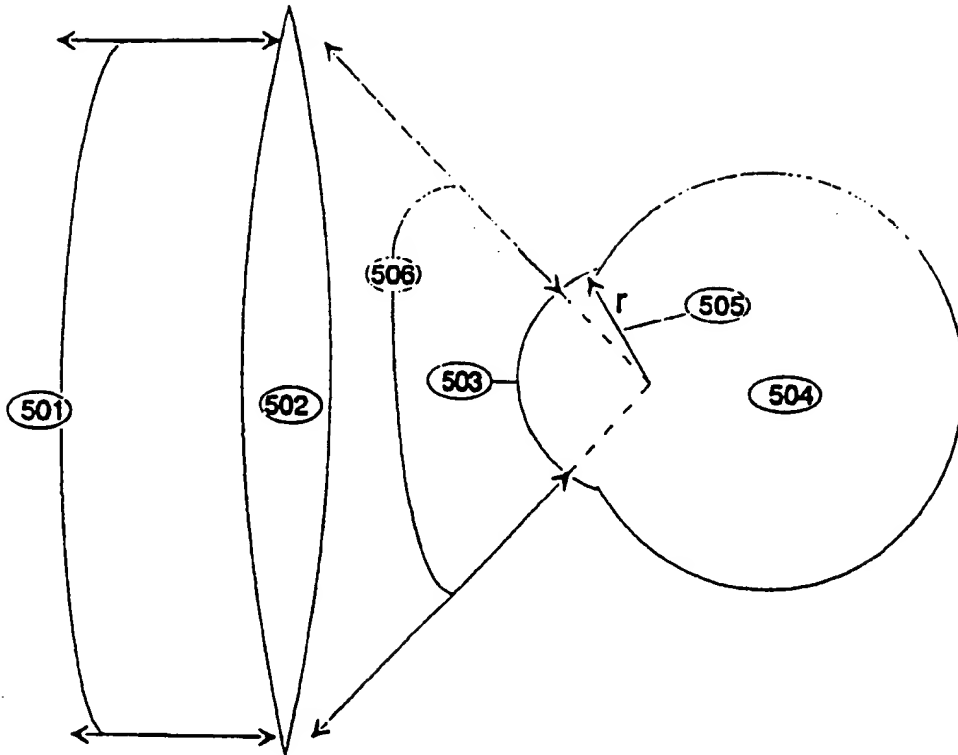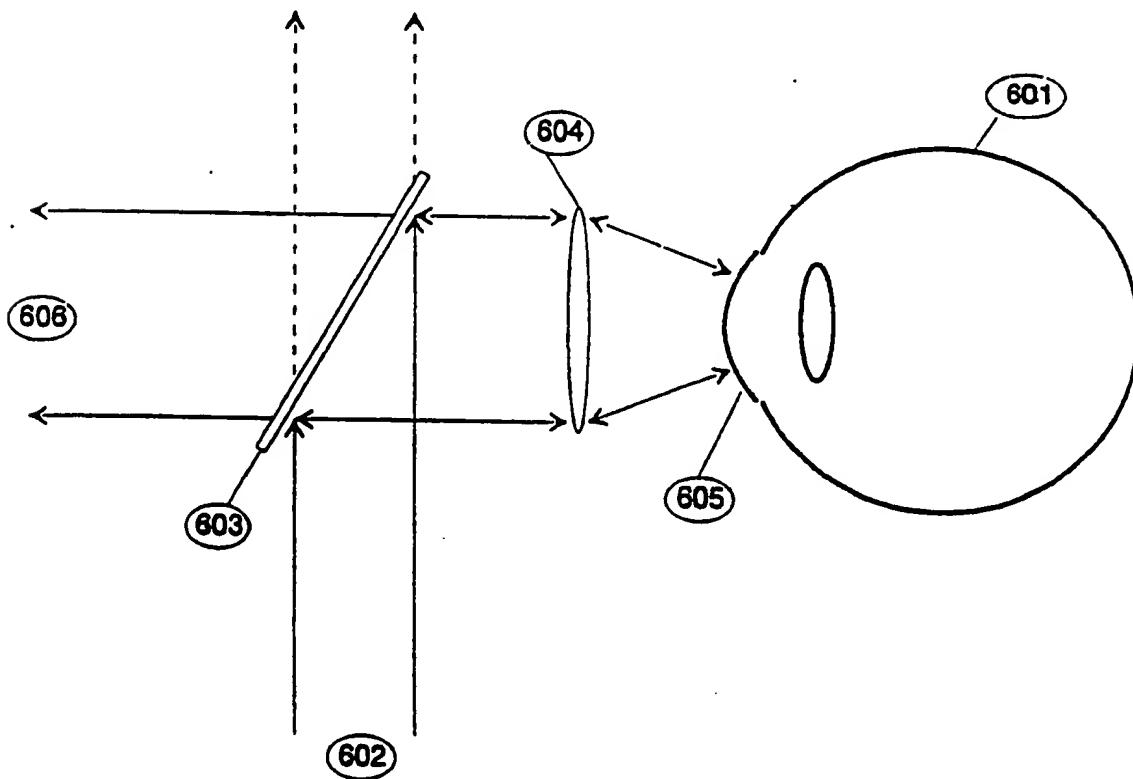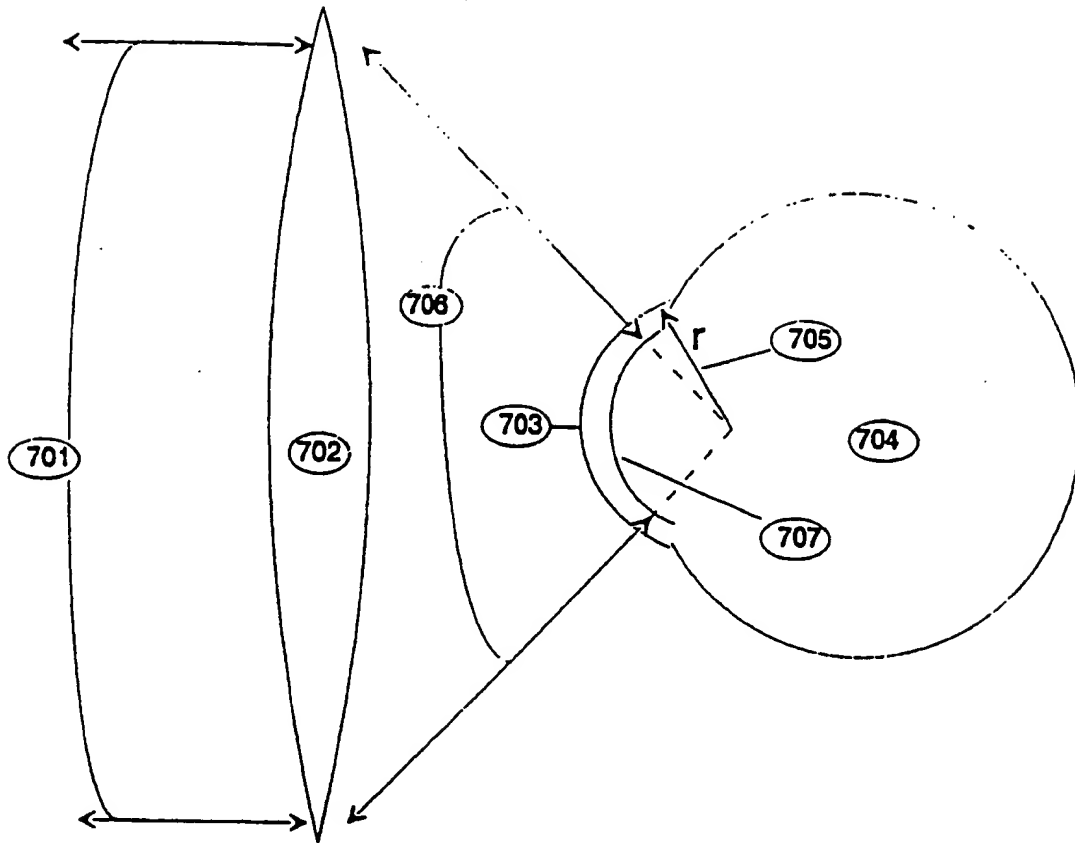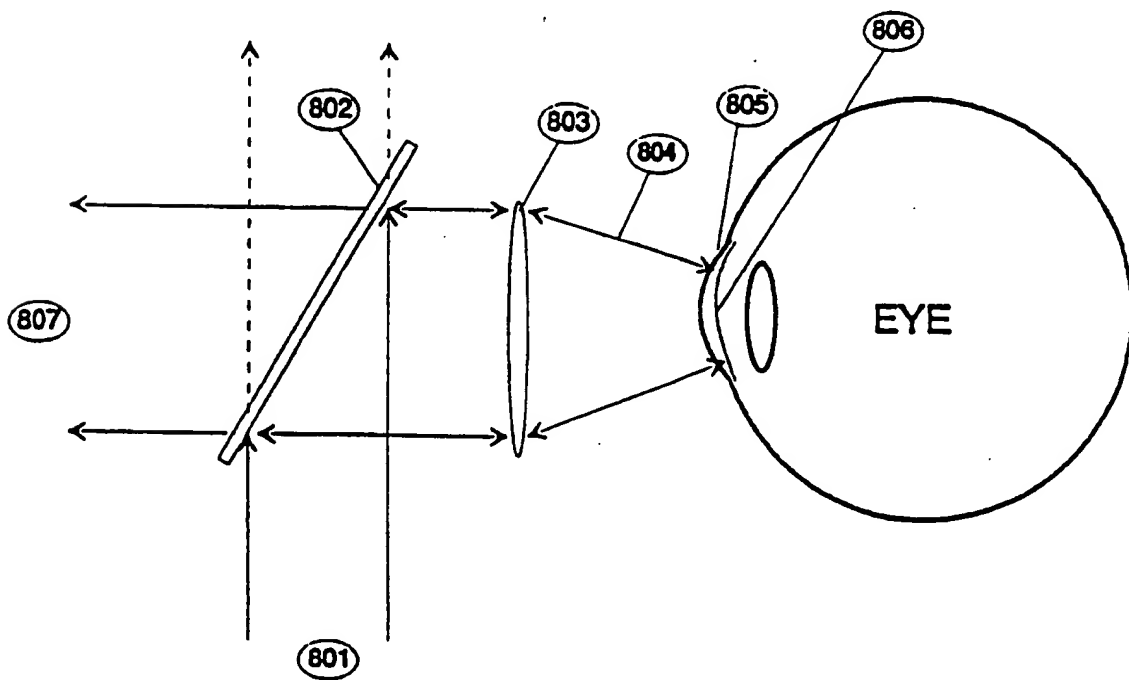
Figure 1

FIGURE 2

FIGURE 3.

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

(1005) (1004)

$\boxed{\begin{array}{c}\text{Filter}\\\text{transfer}\\\text{function}\\\text{computation}\end{array}}$ (1006)

(1003)

$\left|M'_{(x\omega_x, j\omega_y)}\right|^2$

$\boxed{\begin{array}{c}\text{Input Estimation}\\\text{of}\\\text{power spectrum}\end{array}}$

(1002) $S'_{(x\omega_x, j\omega_y)}$

(1007) $H_{(x\omega_x, j\omega_y)} = \dfrac{\left|S'_{(x\omega_x, j\omega_y)}\right|^2}{\left|M'_{(x\omega_x, j\omega_y)}\right|^2}$

$\boxed{\begin{array}{c}\text{Signal}\\\text{Spectral}\\\text{estimation}\\f_0 = p/(2\sin 0)\end{array}}$

(1000) (1001)

(1008) $P_{(x\omega_x, j\omega_y)}$ (1010) OUTPUT
moire'
pattern

Input moire'
pattern
m(x,y) $\boxed{\begin{array}{c}\text{Fourier}\\\text{Transform}\end{array}}$ $M_{(x\omega_x, j\omega_y)}$ $\boxed{\begin{array}{c}\text{Complex}\\\text{Multiply}\end{array}}$ $\boxed{\begin{array}{c}\text{Inverse}\\\text{Fourier}\\\text{transform}\end{array}}$ noise
&
background
reduced
p(x,y)

(1009)

(1011)

Figure 10

(1111) (1113) (1115) (1117) (1118)

(1112) (1114) (1116)

p(x,y)
moire'
pattern
w/reduced
noise & background $\boxed{\begin{array}{c}\text{Determine}\\\text{Centroid}\\\&\\\text{variance}\\\text{for all p(x,y)}\end{array}}$ $\boxed{\begin{array}{c}\text{Determine}\\\text{window}\\\text{size}\\\text{at}\\\overline{\sigma}\end{array}}$ $\boxed{\begin{array}{c}\text{Pass window}\\\text{throughout}\\\text{all of}\\\text{p(x,y)}\end{array}}$ $\boxed{\begin{array}{c}\text{Within each}\\\text{window}\\\text{determine}\\\text{p(max) \& p(min)}\end{array}}$

(1119)

OUTPUT:
p'(x,y)
moire' pattern
perfectly suited
for wave front
analysis
and
pattern
tracking

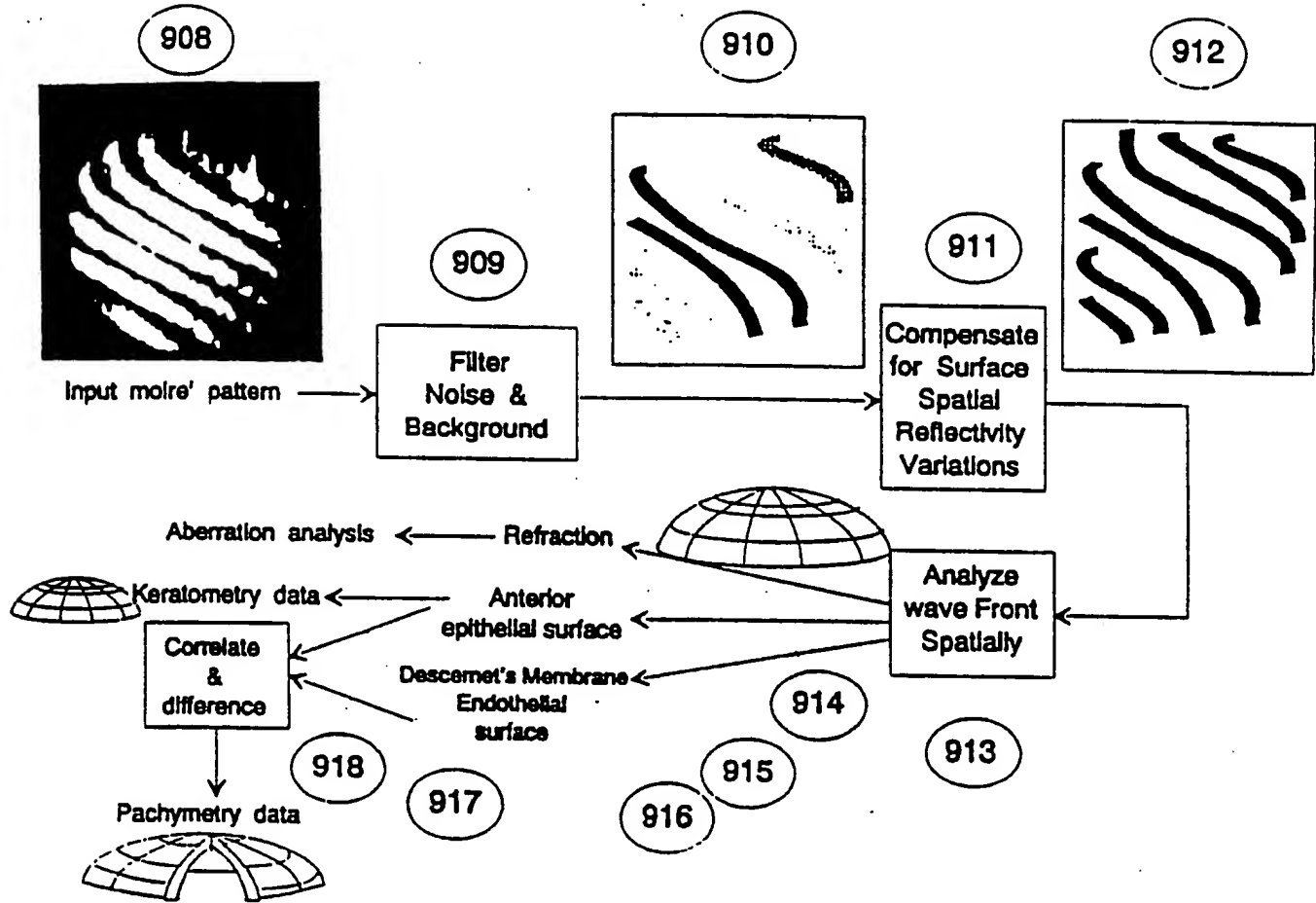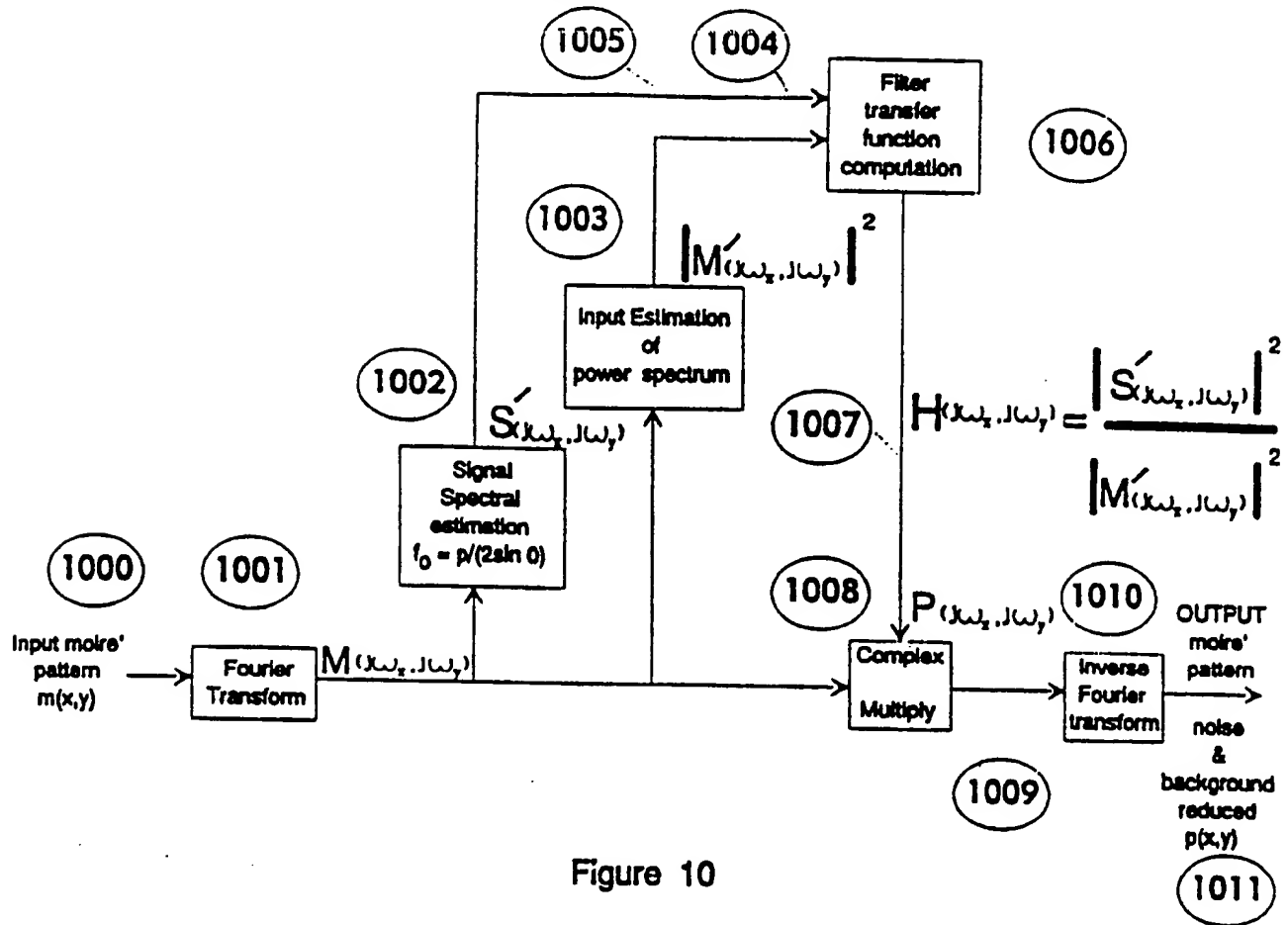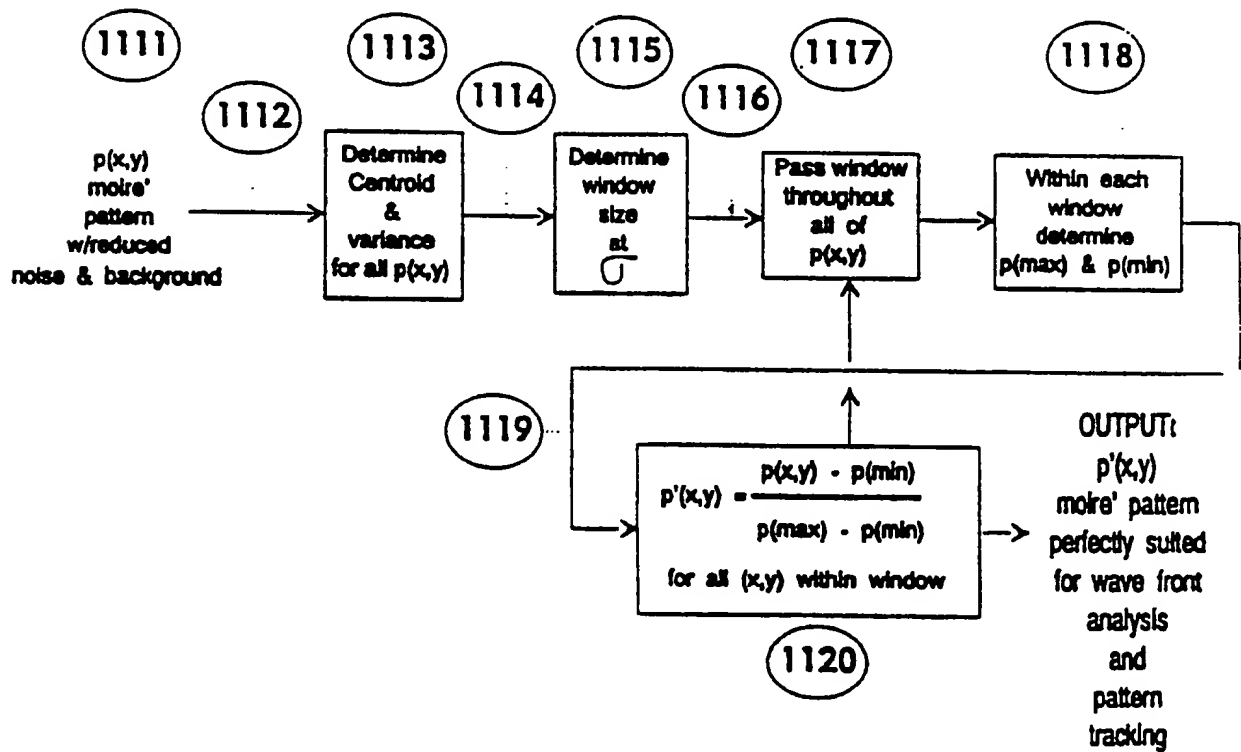$\boxed{\begin{array}{c}p'(x,y) = \dfrac{p(x,y) - p(min)}{p(max) - p(min)}\\\text{for all (x,y) within window}\end{array}}$
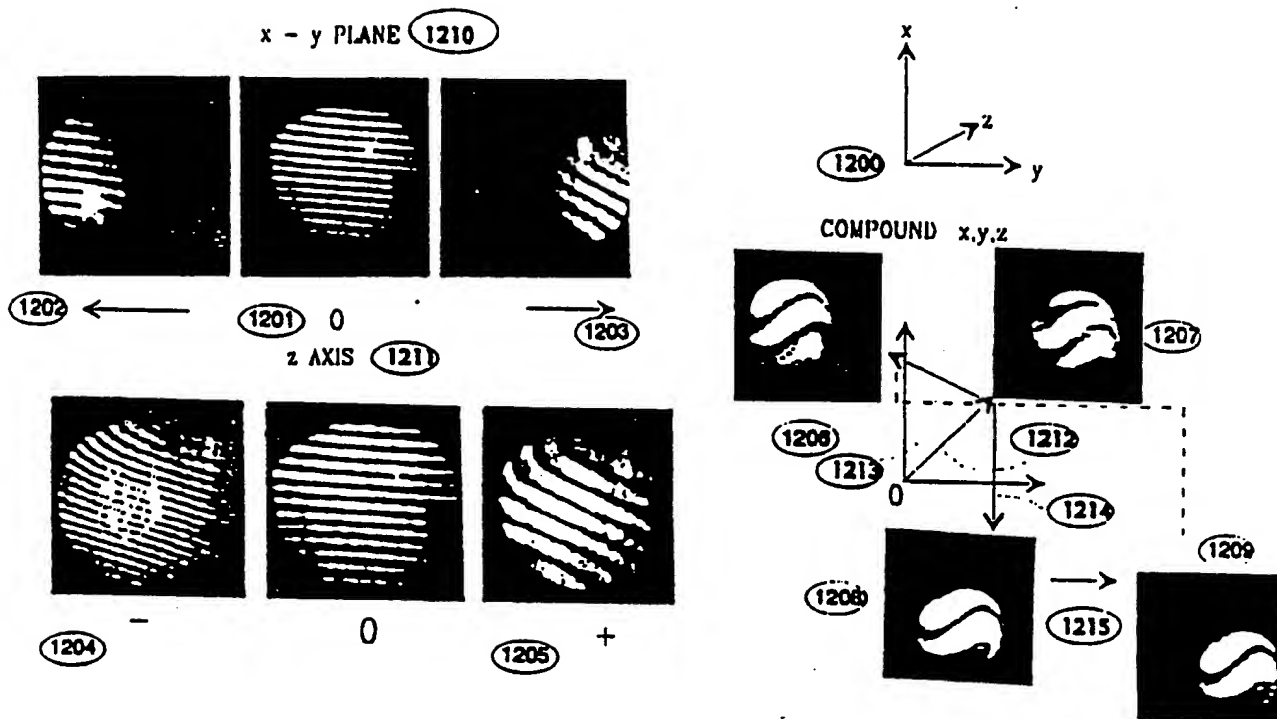
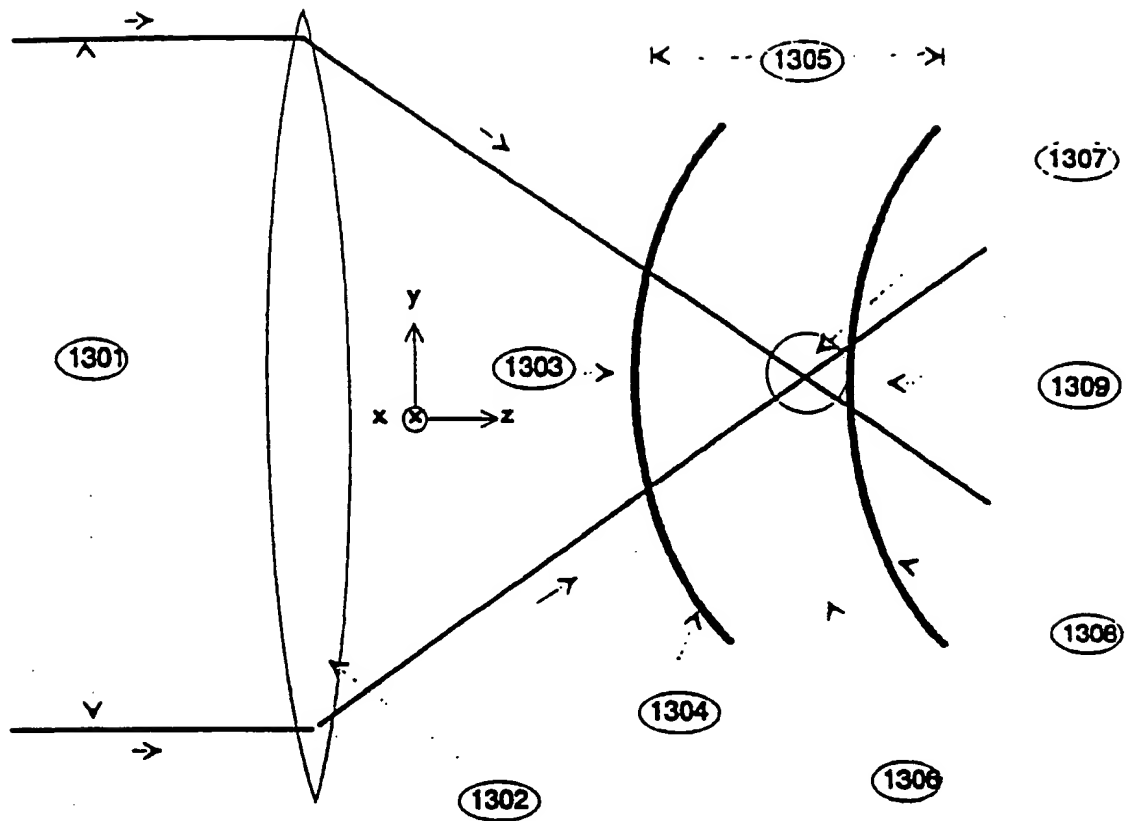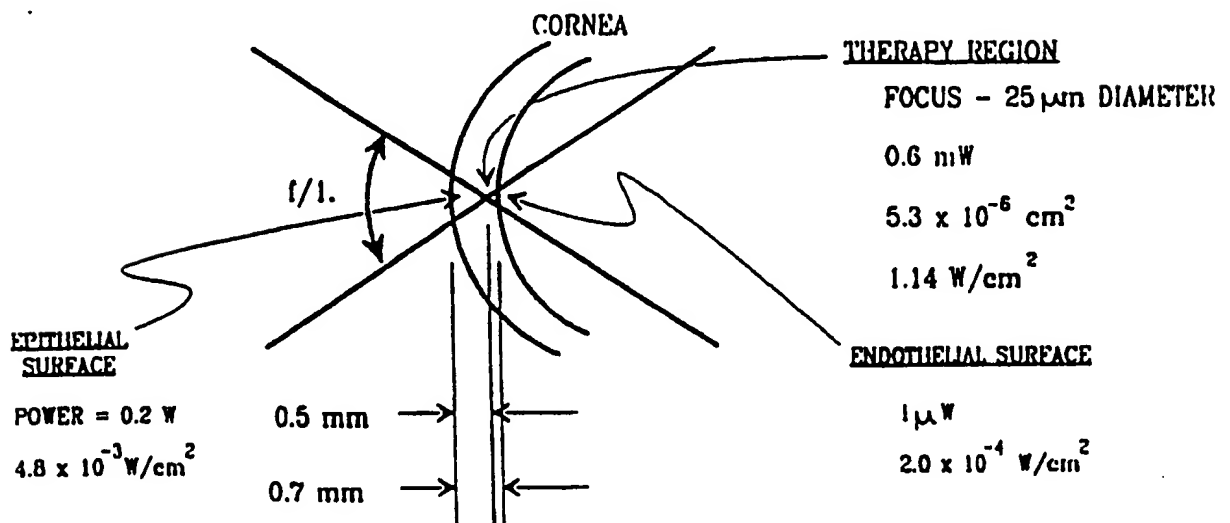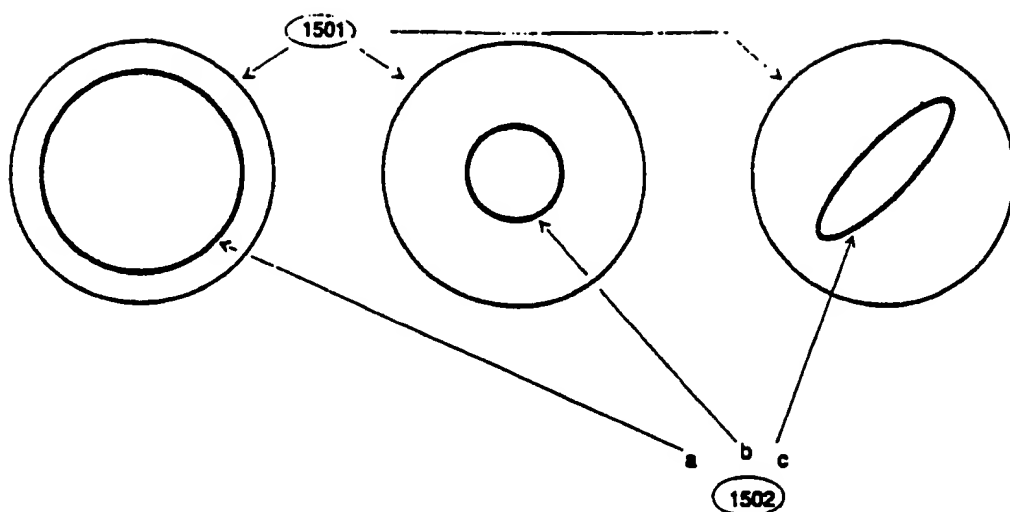(1120)

Figure 11

Figure 12

Figure 13
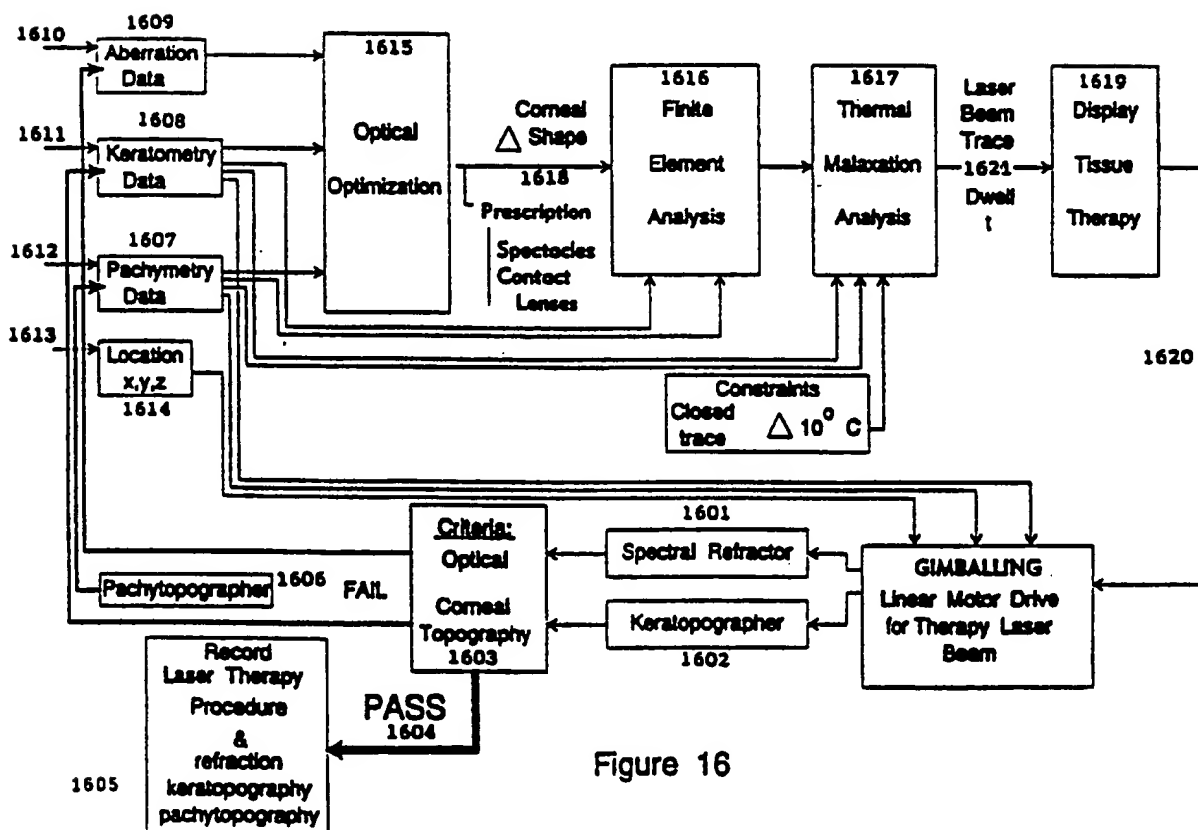

Figure 14

FIGURE 15

Figure 16

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US91/04976

I. CLASSIFICATION F SUBJECT MATTER (if several classification symbols apply, indicate all) *

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5): A61B 3/10
U.S. CL.: 351/212,221

II. FIELDS SEARCHED

Minimum Documentation Searched [7]	
Classification System	Classification Symbols
U.S.	351/212,205,221 128/395

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US,A, 4,692,003 (ADACHI et al.) 08 SEPTEMBER 1987 See entire document	1-30,84-86
X	US,A, 4,721,379 (L'ESPERANCE) 26 JANUARY 1988 See especially cols. 5-7	57-83,89
A	US,A, 4,964,715 (RICHARDS) 23 OCTOBER 1990 See cols. 2,3	57-83,89
A	US,A, 4,984,883 (WINOCUR) 15 JANUARY 1991 See cols. 3-5	1-30,84-86

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
22 NOVEMBER 1991	04 DEC 1991
International Searching Authority	Signature of Authorized Officer
ISA/US	PAUL M. DZIERZYNSKI

Form PCT/ISA/210 (second sheet) (Rev.11-87)